

# Diffuse far-infrared and ultraviolet emission in the NGC4435/4438 system: tidal stream or Galactic cirrus?

L. Cortese<sup>1\*</sup>, G. J. Bendo<sup>2</sup>, K. G. Isaak<sup>1</sup>, J. I. Davies<sup>1</sup> & B. R. Kent<sup>3</sup>

<sup>1</sup> *School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, UK.*

<sup>2</sup> *Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK.*

<sup>3</sup> *NRAO 520 Edgemont Road, Charlottesville, VA, 22903, USA.*

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## ABSTRACT

We report the discovery of diffuse far-infrared and far-ultraviolet emission projected near the interacting pair NGC4435/4438, in the Virgo cluster. This feature spatially coincides with a well known low surface-brightness optical plume, usually interpreted as tidal debris. If extragalactic, this stream would represent not only one of the clearest examples of intracluster dust, but also a rare case of intracluster molecular hydrogen and large-scale intracluster star formation. However, the ultraviolet, far-infrared, H I and CO emission as well as the dynamics of this feature are extremely unusual for tidal streams but are typical of Galactic cirrus clouds. In support to the cirrus scenario, we show that a strong spatial correlation between far-infrared and far-ultraviolet cirrus emission is observed across the center of the Virgo cluster, over a scale of several degrees. This study demonstrates how dramatic Galactic cirrus contamination can be, even at optical and ultraviolet wavelengths and at high galactic latitudes. If ignored, the presence of diffuse light scattered by Galactic dust clouds could significantly bias our interpretation of low surface-brightness features and diffuse light observed around galaxies and in clusters of galaxies.

**Key words:** galaxies:individual: NGC4435/4438 – galaxies: interactions – ISM: dust.

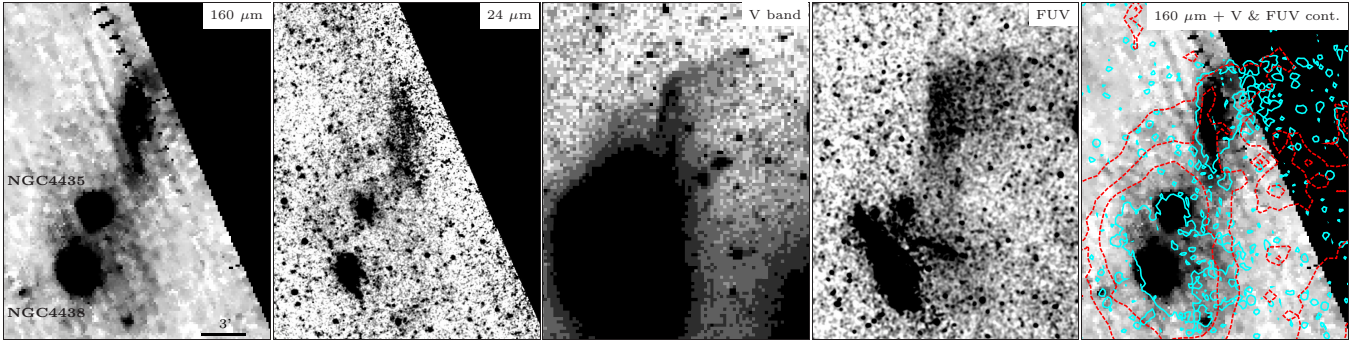
## 1 INTRODUCTION

The study of the diffuse low surface-brightness light around galaxies and within clusters represents a unique tool for understanding the assembly history of structure in the universe. The detection of faint stellar tails associated with apparently undisturbed systems (McConnachie et al. 2009), as well as the presence of diffuse light in galaxy clusters (Mihos et al. 2005), are among the clearest pieces of evidence supporting a hierarchical picture of galaxy formation. In the past, the long integration times (and accurate flat-fielding) required to detect faint features have hampered the search for diffuse extragalactic light. In the next few years, with the advent of dedicated deep optical photometric surveys such as Pan-Starrs and the Next Generation Virgo Cluster Survey, will we eventually obtain an unprecedented view of the complex low surface-brightness universe, reaching very high sensitivities ( $\mu \gtrsim 28$  mag arcsec<sup>-2</sup>). The main challenge for future investigations will likely be discriminating between extragalactic emission and scattered light from Galactic cirrus. At low surface-brightness ( $\mu_B \gtrsim 27$  mag arcsec<sup>-2</sup>), scattered light from cirrus dust clouds is clearly

detected at optical wavelengths even at high galactic latitude (e.g., Guhathakurta & Tyson 1989). This might be erroneously interpreted as tidal debris or intracluster light. To show how difficult it is to discriminate between extragalactic and Galactic low surface brightness features, here we present the properties of a plume projected near the NGC4435/4438 pair in the Virgo cluster. This plume is usually interpreted as a tidal stream (Mihos et al. 2005).

NGC4438 (Arp 120) is the most dramatic example of a tidally disturbed galaxy in the Virgo cluster. Dynamical models suggest that NGC4438 has been perturbed by a high-velocity ( $\sim 800$  km s<sup>-1</sup>) interaction with the companion S0 NGC4435 (e.g., Vollmer et al. 2005). However, recent H $\alpha$  observations favour a different scenario in which NGC4438 has collided with the giant elliptical galaxy M86 (Kenney et al. 2008). Deep optical investigations (Mihos et al. 2005) also reveal the presence of a faint stellar plume apparently extending from NGC4435. This feature has been interpreted in the past as a tidal debris, but it is not clear how it would fit into the NGC4438-M86 interaction scenario. In this Letter, we show that the multi-wavelength properties of the optical plume are more similar to Galactic cirrus clouds than to tidal debris and that this

\* luca.cortese@astro.cf.ac.uk



**Figure 1.** From left to right, the Spitzer MIPS  $160\mu\text{m}$ ,  $24\mu\text{m}$ , V-band (Mihos et al. 2005) and GALEX-FUV images are shown. In the right panel, the optical (dashed red) and FUV (solid cyan) contours are superposed to the  $160\mu\text{m}$ . The contour levels are  $25.5$ ,  $26.5$ ,  $27.5$  mag arcsec $^{-2}$  and  $29.8$  AB mag arcsec $^{-2}$  in V and FUV, respectively. The  $24\mu\text{m}$  and FUV images have been smoothed using a gaussian filter with  $\sigma = 3$  pixels in order to make the plume more visible.

feature might not be associated with the NGC4435/4438 system at all.

## 2 THE DATA

**Spitzer observations.** We obtained Spitzer MIPS  $24$ ,  $70$  and  $160\mu\text{m}$  observations of the NGC4435/4438 system from the Spitzer Science Archive. These data are all scan maps taken as part of a single proposal (P30945). The image frames were created using the MIPS Data Analysis Tools (Gordon et al. 2005) version 3.10 and using the same technique described in Bendo et al. (2009). The rms in the final maps are  $0.037$ ,  $0.38$  and  $0.39$  MJy sr $^{-1}$  at  $24$ ,  $70$  and  $160\mu\text{m}$ , respectively. The full widths at half maximum (FWHM) of the PSFs are  $6$ ,  $18$  and  $38$  arcsec at  $24$ ,  $70$  and  $160\mu\text{m}$ , respectively.

**Ultraviolet imaging.** The Galaxy Evolution Explorer (GALEX) has observed the NGC4435/4438 system in both near- (NUV,  $\lambda = 2316$  Å,  $\Delta\lambda = 1069$  Å) and far-ultraviolet (FUV,  $\lambda = 1539$  Å,  $\Delta\lambda = 442$  Å) bands, as part of the Nearby Galaxy Survey. Two different tiles include the two galaxies and the stellar tail. We downloaded the final intensity maps from the MAST archive (GR4/5) and coadded them, reaching a total exposure time of  $7628.35$  and  $2967.8$  sec in the NUV and FUV bands, respectively. The spatial resolution of the final images is  $\sim 5''$ . Details about the GALEX pipeline can be found in Morrissey et al. (2007).

**Single-dish 21 cm H I line data.** Single-dish H I observations of the NGC4435/4438 system were obtained as part of the Arecibo Legacy Fast ALFA (ALFALFA) survey (Giovanelli et al. 2005). The dataset used here comes from the first ALFALFA data-release (Giovanelli et al. 2007), covering the center of the Virgo cluster. The total integration time is  $48$  sec beam $^{-1}$ , providing an rms of  $\sim 2.2$  mJy beam $^{-1}$  at a velocity resolution of  $\sim 10$  km s $^{-1}$ . The data are gridded into a data cube with  $1'$  pixels and the spatial resolution is given by the size of the Arecibo beam,  $3.3' \times 3.8'$ .

**Single-dish CO(2-1) observations.** To detect CO(2-1) associated with the stellar tail, we have carried out a pilot observation using the single-pixel A3 receiver (beam-width  $\sim 22''$ ) at the James Clerk Maxwell Telescope (JCMT<sup>1</sup>).

We used the full bandwidth of  $\sim 1.9$  GHz ( $-500 \lesssim V_{\odot} \lesssim 1900$  km s $^{-1}$ ), thus covering the entire velocity range between NGC4435 and NGC4438 ( $\sim 800$  km s $^{-1}$ ), with a velocity resolution of  $\sim 1.3$  km s $^{-1}$ . A simple ON-OFF observing technique was adopted. The ON position roughly corresponds to the peak of  $160\mu\text{m}$  emission in the stream ( $\alpha_{J2000}=12:27:30.2$ ,  $\delta_{J2000}=+13:12:29$ ), while the OFF position was accurately chosen in order to avoid any possible contamination from Galactic emission. Data were reduced using the Starlink data reduction packages (KAPPA and SMURF). Individual spectra were inspected and then coadded to produce a final spectrum with a total on-source integration time of  $1347$ s. The rms on the final baseline-subtracted spectrum is  $\sim 0.018^{\circ}$  K (expressed in antenna temperature).

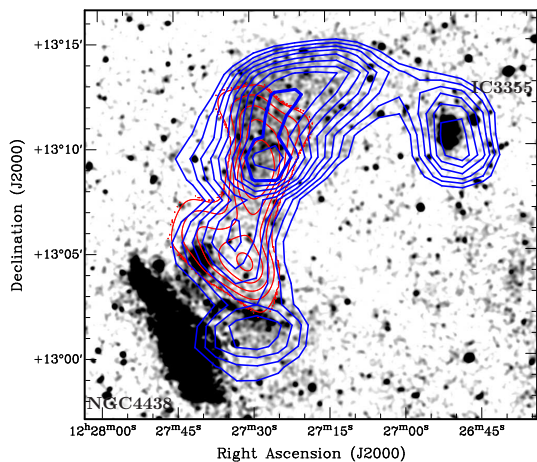
## 3 RESULTS

In Fig. 1, we compare the Spitzer  $24$  and  $160\mu\text{m}$  images, the GALEX FUV image, and the deep V-band image obtained by Mihos et al. (2005) for the NGC 4435/4438 system. They clearly reveal the presence of far-infrared and far-ultraviolet diffuse emission associated with the low surface-brightness ( $\mu_V \sim 26.5$ – $28$  mag arcsec $^{-2}$ ) optical plume to the north/north-west of NGC4435 originally discovered by Malin (1994). While the MIPS field of view only includes the brightest part of this feature (close to NGC4435), the larger area covered by GALEX allows us to trace the whole extent of the stream out to a distance of  $\sim 13'$  from NGC4435. The plume has an unusual L-shaped (or triangular) morphology, with abrupt and well defined edges to the east and north. No resolved sources (e.g., star-forming knots) are visible in the plume.

Interestingly, we first noticed the presence of diffuse emission in the Spitzer images, where the intensity of this feature is particularly high:  $\sim 1.5$ – $5$  MJy sr $^{-1}$  and  $\sim 0.05$ – $0.08$  MJy sr $^{-1}$  at  $160$  and  $24\mu\text{m}$ , respectively. A detailed inspection of IRAS images reveals that the plume is marginally

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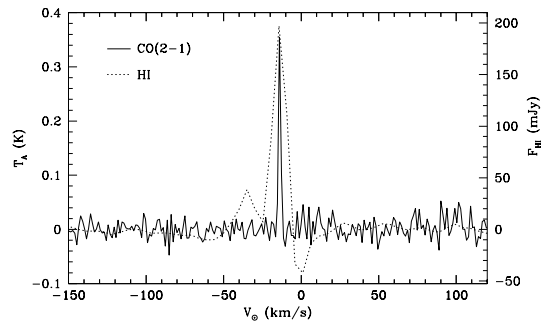
<sup>1</sup> The James Clerk Maxwell Telescope is operated by The Joint



**Figure 2.** The HI contours of the plume superposed on the FUV image. The blue contours show the HI emission detected by ALFALFA (including diffuse Galactic HI) across the heliocentric velocity range  $-9.2 < V_{\odot} < -19.5$  km s $^{-1}$ . Contours levels are 7.2 to 8.2 Jy km s $^{-1}$  beam $^{-1}$ , in steps of 0.1 Jy km s $^{-1}$  beam $^{-1}$ . As discussed in §3, the net HI intensity of the plume has been obtained by performing a median subtraction of the Galactic emission around the feature. For comparison, the VLA contours of the tail published by Hota et al. (2007) are shown in red. We note that part of the HI associated with NGC4438 and IC3355 is not visible given the narrow velocity range here investigated.

visible in the 100  $\mu$ m image, although the lower spatial resolution of IRAS made it impossible to clearly associate the plume with the NGC4435/4438 system. No emission is detected at 70  $\mu$ m, implying a  $3\sigma$  upper limit of  $\sim 1.14$  MJy sr $^{-1}$ . The GALEX data reveal that the plume is really evident in FUV ( $\mu_{FUV} \sim 29$  AB mag arcsec $^{-2}$ ), whereas in NUV it is only very marginally detected at a surface-brightness level of  $\mu_{NUV} \sim 29.2$  AB mag arcsec $^{-2}$ .

In addition to dust and stars, this feature appears also to contain a significant amount of atomic hydrogen and CO. Using the Very Large Array (VLA), Hota et al. (2007) detected HI emission associated with the brightest part of the plume. Intriguingly, the HI has a low recessional velocity ( $\sim -9.5$  km s $^{-1}$ , for a velocity resolution of 20.7 km s $^{-1}$ ) and a narrow velocity width ( $< 40$  km s $^{-1}$ ). Unfortunately, the northern and eastern edges of the tail were too close to the half-power of the VLA primary beam to be detected. Thanks to the higher sensitivity, velocity resolution and larger field of view of ALFALFA observations, we are now able to fill this gap and to characterize in more detail the HI properties of this plume. By inspecting the cube through a velocity range  $-200 < V < 1000$  km s $^{-1}$  (i.e., the typical interval expected if the plume is related to the NGC4435/4438 system), we confirm that the only HI emission clearly associated with the optical plume has a heliocentric velocity  $V_{\odot} = -15 \pm 4$  km s $^{-1}$  and a width  $W_{50} = 5 \pm 7$  km s $^{-1}$ . In Fig. 2 the ALFALFA and Hota et al. (2007) HI contours are superposed to the FUV image of the NGC4435/4438 system. While the two datasets fairly agree in the overlapping region, the ALFALFA observations are able to trace the HI along the whole extent of the plume, showing a good match between the HI and FUV morphology of this feature. To estimate its net HI intensity we performed a median subtraction of the Galactic emission around the plume. The net flux density varies in the



**Figure 3.** The single-pointing CO(2-1) (solid line) and integrated HI (dotted line) spectrum of the plume.

range 0.6–1.2 Jy km s $^{-1}$  beam $^{-1}$ . Assuming that the HI fills the Arecibo beam, this can be translated into a column density of  $\sim 1.5\text{--}3 \times 10^{19}$  cm $^{-2}$  (see also Hota et al. 2007). The integrated HI spectrum of the plume<sup>2</sup> is shown in Fig. 3. The peak and absorption features on either side of the detection are residual artifacts of the sky subtraction based on the median values in the selected channels. The recessional and velocity widths of the plume are confirmed, and even better constrained, by our CO(2-1) observations, as shown in Fig. 3. CO(2-1) emission is clearly detected (peak signal-to-noise  $\sim 20$ ) at a heliocentric velocity  $V_{\odot} = -13.9 \pm 0.1$  km s $^{-1}$  and with a  $FWHM = 1.5 \pm 0.2$  km s $^{-1}$ .

In summary, the plume shows emission coming not only from stars and atomic hydrogen but also dust and CO, emerging as an almost unique feature in the panorama of low surface-brightness streams and tails discovered so far in the Virgo cluster.

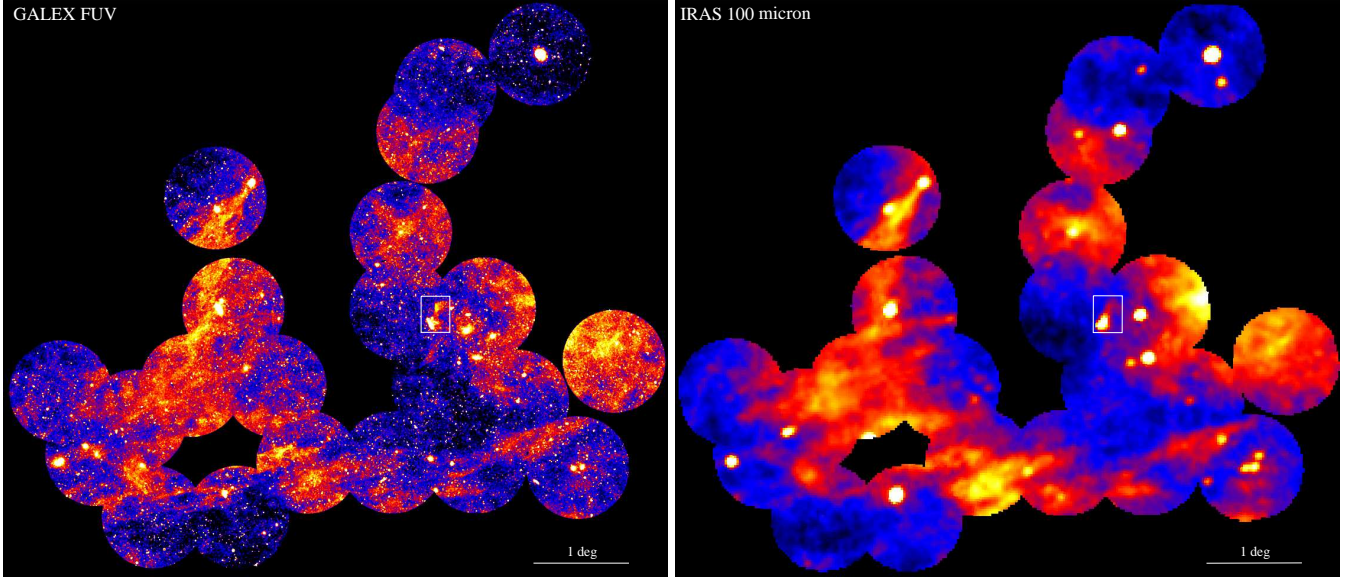
## 4 DISCUSSION

What is the nature of this plume? Is it really a tidal stream associated with the NGC4435/4438 system? If extragalactic, it would represent an extremely rare example of intracluster dust and molecular hydrogen stripped by gravitational interactions. However, the multiwavelength properties of this feature demand a little bit of attention before one can interpret it as a tidal feature. This is particularly true since the plume is detected in far-infrared, where the contamination from foreground Galactic cirrus emission might be significant, if not dominant. In the following, we investigate the two possible scenarios (tidal stream and Galactic cirrus) in order to unveil the most likely origin of this feature.

### 4.1 The tidal scenario

If at the distance of the Virgo cluster (16.5 Mpc, Mei et al. 2007), the plume would have a physical size of  $\sim 33$  kpc (in both right ascension and declination), extending up to  $\sim 70$  kpc from NGC4438. Its HI and CO recessional velocities ( $\sim -14$  km s $^{-1}$ ) are roughly consistent with the HI velocity of NGC4438 ( $V_{\odot} = 104 \pm 2$  and  $W_{50} = 244 \pm 5$  km s $^{-1}$ , Giovanelli et al. 2007) but significantly different from the

<sup>2</sup> We only considered the main HI feature visible Fig.2: i.e., the one clearly associated with the optical, UV and far-infrared plume.



**Figure 4.** The Virgo cluster region as seen in FUV (left) and 100  $\mu\text{m}$  (right). The region shown in Fig. 1 is indicated by the white rectangle. The FUV mosaic have been smoothed using a gaussian filter with  $\sigma = 9$  pixels in order to highlight the diffuse cirrus emission.

redshift of NGC4435 ( $V \sim 801 \text{ km s}^{-1}$ ). This apparently rules out a gravitational interaction between NGC4438 and NGC4435: given their large velocity difference, we should expect the stripping material to lie at a velocity intermediate between the two systems.

The plume apparently connects NGC4438 to the dwarf irregular galaxy IC3355 ( $V \sim -17 \text{ km s}^{-1}$ , Gavazzi et al. 2003), perhaps suggesting a recent interaction between the two systems. This seems supported by the presence of a H I tail associated with IC3355 (Chung et al. 2009). However, contrary to what expected in case of a fly-by encounter with NGC4438, IC3355’s tail points to the west, thus in the opposite direction with respect to NGC4438. Moreover, it is still unclear whether or not IC3355 is really a member of the M86 cloud (Chung et al. 2009). Thus, although we cannot exclude that IC3355 is playing a role, the current data do not allow us to further investigate this hypothesis.

A more plausible scenario is that the plume has been created during the collision between NGC4438 and M86 ( $V \sim -244 \text{ km s}^{-1}$ ) as recently unveiled by Kenney et al. (2008). A complex structure of H $\alpha$  filaments connects the two galaxies and spans a velocity range ( $-240 < V < +70 \text{ km s}^{-1}$ ) consistent with the value observed in the plume. Moreover, the morphology of our feature (i.e., well defined edges on the east with less clear boundaries on the west side) would be consistent with the direction of motion of NGC4438, from west to east. The time-scale of the interaction is  $\sim 100 \text{ Myr}$  (Kenney et al. 2008), significantly shorter than the dust sputtering time-scale expected at the position of NGC4438 ( $\sim 10^8 \text{ yr}$ ; Popescu et al. 2000). Thus, although extremely unusual, the presence of dust in the tail does not rule out the tidal scenario.

However, not all the properties of the plume are entirely consistent with a gravitational interaction. Above all, its velocity width ( $\sim 2\text{--}5 \text{ km s}^{-1}$ ) is significantly smaller than the typical values ( $\geq 20 \text{ km s}^{-1}$ ) observed in tidal tails, candidate tidal-dwarf galaxies, isolated H I clouds and ram pres-

sure stripped material (e.g., Hibbard et al. 2001; Kent et al. 2007; Oosterloo & van Gorkom 2005). Although we cannot exclude that the cloud is seen ‘face-on’, we consider this to be unlikely. The presence of a clear velocity gradient in the H $\alpha$  filaments between M86 and NGC4438 (Kenney et al. 2008) suggests in fact that the tidal acceleration is not parallel to the plane of sky. Moreover, it is difficult to imagine how a violent process such as a tidal interaction would be able to strip material along a well defined direction and to keep the velocity dispersion of the H I cloud so small. It is therefore unclear how tidal debris can maintain such small velocity spread on a scale of a few tens of kpc.

Equally unusual are the UV properties of the tail. The FUV emission is in fact diffuse and not patchy with star-forming knots as observed in star-forming disks, tidal tails and extended UV disks (e.g., Thilker et al. 2007). Extraplanar diffuse UV emission is often interpreted as being due to light scattered by diffuse dust, in particular when associated with the halos of starburst galaxies (like M82; Hoopes et al. 2005). Although the Spitzer images reveal that dust is surely present in the plume, the lack of a powerful central starburst and the large distance of the tail from any strong radiation source apparently exclude the scattering scenario. Thus, if extragalactic, the FUV emission must come from young stars in the plume. The absence of star-forming knots and H $\alpha$  emission (Kenney et al. 2008) implies an age between  $\sim 10 \text{ Myr}$  (i.e., the lifetime of OB associations emitting in H $\alpha$ ) and  $\sim 25 \text{ Myr}$  (i.e., the lifetime of B stars, supposed to be responsible for the diffuse UV light in galactic disks; Pellerin et al. 2007), significantly shorter than the time-scale of the interaction but consistent with the age of the UV tidal tail to the west of NGC4438 discovered by Boselli et al. (2005). This might suggest that the plume has just entered a post-starburst phase, consistent with the fact that its colour is significantly bluer than the observed colour of NGC4438 ( $FUV - V \sim 5.2 \text{ mag}$ ; Gil de Paz et al. 2007). However, if this is really the case, it remains unclear

to us why the plume stopped forming stars. The very low velocity dispersion, the large amount of HI and the presence of molecular hydrogen should allow the cloud to continue forming stars. Moreover, the fact that CO is usually associated with dense star-forming regions, even in tidal tails and stripped clouds (Lisenfeld et al. 2004), makes the post-starburst scenario unlikely.

## 4.2 The Galactic cirrus hypothesis

A completely different possibility is that the plume is in reality a Galactic cirrus cloud of gas and dust just superposed by chance near NGC4435. In this case, the diffuse FUV and optical emission would come from light scattered by the dust grains in the cloud.

Before testing the cirrus hypothesis in detail, it is worthwhile to examine the probability of a cirrus cloud appearing superimposed in front of the Virgo cluster. Despite its high Galactic latitude ( $b \sim 75^\circ$ ), the center of Virgo lies in a region that is significantly contaminated by cirrus emission. A ring-like cirrus structure centered near M87 and extending over several degrees (Brosch et al. 1999) is clearly visible in the IRAS  $100\mu\text{m}$  images (see Fig. 4, right). Since scattered light is often associated with cirrus clouds (e.g., Guhathakurta & Tyson 1989), we should expect to see the same ring at both ultraviolet and optical wavelengths, though only at very low surface-brightness ( $\mu_B \sim 27\text{--}28$  mag arcsec $^{-2}$ ). While deep optical data of the whole Virgo region are not available, the deep and wide GALEX coverage of the Virgo cluster makes it possible to test this hypothesis. We thus combined all the available GALEX pointings near the center of Virgo having FUV exposure time longer than 800 sec. The mosaic is shown in the left panel of Fig. 4, and it likely represents the highest resolution large-scale map of FUV cirrus emission made to date. It clearly illustrates the presence of diffuse FUV emission tracing the distribution of far-infrared Galactic cirrus emission. In addition the high spatial resolution of GALEX allow us to see for the first time the detailed structure of the cirrus clouds. In order to quantify the correlation between FUV and FIR diffuse emission, we first removed all sources detected by Sextractor (Bertin & Arnouts 1996) and then smoothed the UV images to the resolution of the ‘point-source free’ Schlegel et al. (1998) IRAS map ( $\sim 6$  arcmin) by applying a Gaussian filter. The Pearson correlation coefficient between the FIR and UV intensity in each pixel ( $142 \times 142$  arcsec $^2$ ) is  $\sim 0.82$ , consistent with the range of values obtained by previous analysis of cirrus clouds (e.g., Haikala et al. 1995; Sasseen & Deharveng 1996). Thus, there is a reasonably high probability of detecting diffuse scattered far-ultraviolet (and perhaps also optical) light associated with cirrus emission in the direction of the Virgo cluster.

More direct support to the cirrus hypothesis is provided by the properties of the plume. Its negative recessional velocity, narrow velocity width and HI column density are completely consistent with what is observed in Galactic low-velocity clouds (e.g., Stanimirović et al. 2006). In addition, the presence of CO emission (and thus of molecular hydrogen) is commonly observed in cirrus clouds (Reach et al. 1998).

Several studies have shown that there is a good correlation between the  $100\mu\text{m}$  far-infrared intensity and the HI col-

umn density of cirrus clouds: e.g.,  $I(100\mu\text{m})/N(\text{HI}) \sim 0.5\text{--}3$  MJy sr $^{-1}$  /  $10^{20}$  cm $^2$  (Boulanger et al. 1996). At  $160\mu\text{m}$ , the far-infrared to HI ratio of the plume is  $\sim 10$  MJy sr $^{-1}$  /  $10^{20}$  cm $^2$ . Assuming a typical 160 to  $100\mu\text{m}$  flux ratio  $\sim 1.5\text{--}3$  for cirrus clouds (Bot et al. 2009), our feature appears to have a significant far-infrared excess. This is however not inconsistent with the cirrus hypothesis since Galactic ‘far-infrared excess clouds’ are not rare at high Galactic latitudes and, as observed in this case, they are usually associated with significant CO emission (Reach et al. 1998). Thus, the far-infrared-to-HI ratio does not allow us to conclusively discriminate between the two proposed scenarios. This is also because our knowledge of the gas and dust content of cirrus is mainly based on studies of physical scales of tens of arcminutes, and it is not yet clear whether we can extrapolate them to the physical scale of the plume.

## 5 CONCLUSION

In this Letter, we have investigated the multiwavelength properties of the optical plume projected near the NGC4435/4438 system. It is very tempting to interpret this feature as tidal debris in the Virgo cluster, as this would represent an extraordinary case of intracluster dust and molecular hydrogen as well as large-scale intracluster star formation. However, our analysis reveals that the dynamics, morphology, gas and dust content of this stream are more consistent with what observed in Galactic cirrus clouds than in tidal features associated with cluster galaxies. Whatever its real origin, this stream is a fascinating object and it clearly highlights how difficult is to discriminate between Galactic clouds and extragalactic diffuse light. This will be a great challenge for both far-infrared Herschel surveys and deep optical investigations of the extragalactic sky. Only a detailed characterization of the FUV-to-far-infrared properties of cirrus at all physical scales might eventually allow us to disentangle between the two different scenarios.

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